Decay Scheme of $^{79}$As

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The $\gamma$-transitions in $^{79}$Se following the decay of $^{79}$As were investigated with a Ge(Li) detector. Six previously unreported $\gamma$-transitions were observed and energy and intensity measurements on eleven $\gamma$-rays are reported. A new decay scheme is proposed which incorporates all the observed $\gamma$-rays. Results concerning the decay schemes of some isotopes of selenium (81 and 73) are also presented.

1. Introduction and Experimental Techniques

Some information about the levels of $^{79}$Se has been obtained by (d, p) and (d, t) reactions. The decay of 9 min $^{79}$As has been studied by KUROYANAGI and his proposed decay scheme as well as a more complete level scheme including reaction data are presented and discussed in Nuclear Data. Many inconsistencies are very obvious and it was thought worth-while to reinvestigate the decay of $^{79}$As.

The $^{79}$As was prepared by irradiating metallic Se (enriched to 97.8% in $^{80}$Se) in the linear accelerator of the C.B.P.F. The maximum energy of the bremsstrahlung beam was 22 MeV and irradiations were performed using up to 600 mg samples with irradiation times up to 30 min.

The gamma-ray spectra were detected by a 2 cm$^3$ Ge(Li) diode. The pulses were fed via an ORTEC 109 preamplifier into an ORTEC 410 amplifier and displayed on a 4096 channel Intertechnique analyser. The overall resolution (FWHM) of the system was 4 keV for the photopeak of the 662 keV line of $^{137}$Cs.

2. Results

The gamma transitions observed by KUROYANAGI were identified with the following energies: 95.5 keV, 364.5 keV, 432.0 keV, 723.6 keV and 878.5 keV. A gamma-ray of 540 keV given in Ref. was not observed in the present work. The following transitions were observed for the first time: 402.3 keV, 446.8 keV, 476.0 keV, 552.0 keV, 715.0 keV and 993.4 keV. The relative photon intensities are given in Table 1. Fig. 1 gives a typical pulse-height spectrum taken for 5 min starting 4 min after the end of the irradiation.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>$\gamma$-Intensity</th>
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<tbody>
<tr>
<td>95.5 ± 0.5</td>
<td>1099 ± 100</td>
</tr>
<tr>
<td>364.5 ± 0.5</td>
<td>125 ± 4</td>
</tr>
<tr>
<td>402.3 ± 0.7</td>
<td>6.5 ± 1.5</td>
</tr>
<tr>
<td>432.0 ± 0.5</td>
<td>100 ± 2</td>
</tr>
<tr>
<td>446.8 ± 0.5</td>
<td>17.5 ± 2.0</td>
</tr>
<tr>
<td>476.0 ± 0.5</td>
<td>24.0 ± 2.5</td>
</tr>
<tr>
<td>552.0 ± 0.7</td>
<td>9.0 ± 1.6</td>
</tr>
<tr>
<td>715.1 ± 0.5</td>
<td>20.0 ± 2.0</td>
</tr>
<tr>
<td>723.6 ± 1.0</td>
<td>7.6 ± 0.8</td>
</tr>
<tr>
<td>878.5 ± 0.3</td>
<td>94 ± 4</td>
</tr>
<tr>
<td>993.4 ± 0.9</td>
<td>8.8 ± 2.5</td>
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</table>

Table 1. Energies and intensities of the gamma-rays found in the decay of $^{79}$As. Intensities are arbitrarily normalized to $I_{\gamma}$ (432 keV) = 100.

Some peaks from the decay of $^{81}$Se are present in the spectrum shown in Fig. 1. Indeed, ($\gamma$, n) reactions on the even mass isotopes of Se are by far the most important source of contamination since the maximum energy available in our accelerator is not big enough to give a favorable $\sigma(\gamma, p)/\sigma(\gamma, n)$ ratio. In particular, the direct formation of $^{79}$Se and the fact that the halflives of this isomer and that of $^{79}$As are of the same order of magnitude is a major difficulty when we try to compare relative intensities of the 96 keV transition with the other transi-

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tions we find in the decay of $^{79}$As. A series of spectra obtained at least 50 min after irradiation was used for this purpose. The decay curve starting at this point shows a negligible contribution of the 4 min activity. Another source of error in the determination of the relative intensity of the 95.5 keV transition is the absence of a direct measurement of the total internal conversion coefficient of this transition. Since the measured $^4$ ratio $\varepsilon_k/\gamma$ for the isomeric transition agrees very well with the calculated values $^5,^6$ of $2\varepsilon_k$, the theoretical value of $\alpha_{tot} = 10.0$ was used to determine the relative transition intensity. An overestimated relative error of about 10% is given for this intensity.

The revised decay scheme deduced from our data is given in Fig. 2. Levels given in Ref. $^2$ at 0.46 MeV and 0.83 MeV were suppressed and new levels at 571.5 keV, 1079.5 keV and 1088.5 keV are suggested. These new levels are indicated by broken lines and shall be discussed in the next section. They are included in order to incorporate all the observed transitions in the decay scheme.

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Partial half-lives of the beta branches indicate odd parity and spin ranging from 1/2 to 5/2 for all the levels directly populated by the beta decay. Introducing further some restrictions on the l value indicated by the reaction data we obtain the quantum numbers given in Fig. 2.

3. Discussion of the Results

From simple shell model considerations we expect the neutrons in the region 28 < N < 50 to be filling the p 3/2, f 5/2, p 1/2 and g 9/2 orbitals. For the 45 neutrons of 76Se the 1/2− and 9/2+ states must appear as the ground and/or the first excited state. Surprisingly, the measured 7/2− ground state of 79Se is 7/2 and its parity is unambiguously given as positive. Such 7/2+ states are low-lying isomeric states of 78Se and 80Se. More generally, this state is a common feature in almost all 41 < Z < 47 nuclei. A possible coupling scheme which would result in a low-lying 7/2+ level in these nuclei is discussed by Ikekami and Sano. The more natural 9/2+ state appears as an excited state at 135 keV in 79Se and at 294 keV in 81Se. The 135 keV level can not be fed by the beta decay of 79As as otherwise we should observe a possible 135 keV transition.

It is perhaps worth comparing the level scheme of 77Se as given in Ref. with our proposed level scheme of 79Se with some additional levels given by nuclear reactions. The number of levels up to 1.2 MeV in both level schemes is essentially the same and we tried an one — by — one identification. So, the lines connecting levels in Fig. 3 must be regarded as a mere tentative to correlate both spectra. The letter D on the 162 keV level of 77Se and on the 135 keV level of 79Se indicates possible doublets with the presence of a l = 1 level in addition to the indicated l = 4 levels. Concerning the isomeric pair there is no possible doubt, but the situation remains questionable for the other levels.

Thus, for instance, the l = 3 levels that appear at 249 keV in 77Se and at 364.5 keV in 79Se decay predominantly to the 7/2+ states and, on the other hand, the l = 3 level that appears at 440 keV in 77Se and an assigned 5/2− state at 571.5 keV in 79Se are identified one with the other since both are negligibly populated by the beta decay of As and both de-excite predominantly to l = 1 states. We identify also the l = 1 levels at 239 keV in 77Se and at 527.5 keV in 79Se since both are fed by beta branches with essentially the same ft values. The 521 keV l = 1 level in 77Se populated by a beta branch with log ft = 5.2 is identified with the 974.3 keV l = 1 level in 79Se populated by a beta branch with log ft = 6.3. The most intense transitions de-exciting these levels are to the first 1/2− level and to the first 3/2− level, in this order. Identification of the two higher l = 1 levels of 77Se with proposed levels at 1079.5 keV and at 1088.5 keV in 79Se is much more arbitrary. In both nuclei we find below 1 MeV two l = 2 levels (not fed by the beta decay), and some l = 0 states are present around 1 MeV.

The great density of odd parity levels at low energy may be correlated to the minimum reached by the energy of the 2+ state in 76Se and 78Se. In fact the core of the odd mass nuclei in the region from Z = 50 upwards seems to become softer and softer as we go from Ni to Se, through Zn and Ge. Such a situation is discussed by Kisslinger and Kumar for the odd — Z nuclei. If it is correct to describe some low-lying levels in 77,79Se in terms of

quasi-particle-phonon coupling we can understand this multiplicity of levels of equal parity as well as the relatively strong hindrances observed in some allowed $\beta$ transitions. The situation is very similar to that observed in some odd-$A$ isotopes in the region ranging from Sb to Pm$^{10,11}$.

4. Miscellaneous Results Concerning the Decay Schemes of Some Isotopes of Selenium

The existence of a line of 552 keV in the decay scheme of $^{79}\text{As}$, the same energy as that of a transition observed in the decay of $^{81}\text{Se}$, was the main reason to re-examine this last decay scheme. For this purpose we irradiated natural selenium (1 g samples of 99.999% purity) with the bremsstrahlung beam. We observed gamma-rays with energies in keV (and intensities) of $275.6 \pm 0.3 (10.2 \pm 0.3)$, $289.9 \pm 0.3 (8.4 \pm 0.3)$, $538.0 \pm 0.4 (0.64 \pm 0.16)$, $552.1 \pm 0.4 (1.35 \pm 0.20)$, $566.0 \pm 0.4 (3.05 \pm 0.30)$ and $827.7 \pm 0.3 (4.1 \pm 0.5)$. The energy of the isomeric transition $^{81m}\text{Se} \rightarrow ^{81}\text{Se}$ was found to be $103.7 \pm 0.5$ keV. These results are in agreement with those obtained by Rao and Fink$^{12}$. It was not possible to prove that the 290 keV line is double, as suggested by Rao and Fink. These authors proposed a level in $^{81}\text{Br}$ at 538 keV populated by a 290 keV transition from the 828 keV level and being deexcited by a 538 keV transition to the ground state. The following levels of $^{81}\text{Br}$ were confirmed: $275.6 \pm 0.3$ keV ($5/2^-$), $566.0 \pm 0.5$ keV ($3/2^-$) and $827.7 \pm 0.4$ keV ($1/2^-, 3/2^-$). In addition there are below 1 MeV at least three levels not fed by the beta decay of $^{81}\text{Se}$: an isomeric state at about 0.55 MeV ($9/2^+$) and levels at 767.3 keV ($5/2^-, 7/2^-$) and at 836.4 keV observed by Coulomb excitation$^{13}$. We believe that this last level, identified by Robinson$^{13}$ is not the same level as observed in the beta decay at 827.7 keV since a difference of 8.7 keV is far beyond the experimental error in both experiments.

In Fig. 4 we present a portion of the gamma spectrum obtained seven minutes after irradiating the natural selenium at a maximum energy of about 20 MeV. The three gamma rays of 538 keV, 552 keV and 566 keV pertaining to the decay of $^{81m}\text{Se}$, $^{81}\text{Se}$ exhibit a complex half life (18 min + 57 min). The annihilation peak decays also with a complex half-life but the components are now 38 min and 7 h, indicating that it is due to the decay of $^{73m}\text{Se}$. The transition of 558.7 keV pertains to the decay of $^{78}\text{As}$. We observe also in the figure a line of 577.5 keV attributed to the decay of $^{73}\text{Se}$ (38 min).

The sources obtained by irradiating natural selenium exhibit a number of unknown lines with half lives in the range 30—45 min. Poor statistics did not permit to determine with precision these periods and even to distinguish between simple and complex half-lifes. Many of them could be associated with the decay of the 38 min $^{73}\text{Se}$, namely: 253.8 keV, 320.1 keV, 392.3 keV, 401.1 keV, 577.5 keV, 649.5 keV, 976.2 keV, 986.2 keV, 1003 keV, 1076.6 keV, 1104.6 keV, 1171 keV and 11 A. G. DE PINHO, J. M. F. JERONIMO and I. GOLDMAN, Nucl. Phys. A 116, 408 (1968).

10 I. V. GOLDSTEIN, J. M. F. JERONIMO and A. G. DE PINHO (to be published).


The Functional Method in the Theory of Real Gases

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The relations of the theory of real gases which have first been derived by Mayer and his coworkers can be obtained in a simple way by the functional method. In this case the assumption of the pairwise additivity of the intermolecular potential can be dropped. Apart from some new relations for distribution functions the expansion of the direct correlation functions is obtained as a power series in density with coefficients consisting of integrals over Husimi functions.

In a series of papers the functional method has been analysed to derive integral equations for molecular distribution functions. In (I) we have shown that successive applications of functional operations lead to hierarchies of functions and their interrelations. In particular we have found that the Ursell and the Husimi expansions can be expressed in terms of appropriate functional derivatives which in turn generate relations between different hierarchies of integral equations. As these expansions are also used in the theory of real gases developed by Mayer and his coworkers one may suspect that the functional method yields a simple derivation of the Mayer theory.

In the following sections we want to present this derivation showing that it is by far less complicated than that given by Mayer himself. Furthermore, the intermolecular potential is restricted only by the properties required for the existence of the relevant integrals. Moreover, this method leads to some new relations for distribution functions and the density expansions of the direct correlation functions. The coefficients in this power series are cluster integrals over Husimi functions.

1 J. E. Mayer and E. W. Montroll, J. Chem. Phys. 9, 2 [1941].